THE DETERMINATION OF IONOSPHERIC CHARGED PARTICLE TEMPERATURES FROM *IN SITU* MEASUREMENTS

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The recently noticed disagreement between ionospheric charged-particle temperature values obtained from ground-based (incoherent backscatter) and *in situ* (Langmuir probe type) measurements is considered; it is suggested that a main cause of disagreement lies in the poor theoretical basis of present *in situ* measurements. It is pointed out that the usually neglected geomagnetic field influence may result in too high an electron temperature. It is also shown that the theory used at present to interpret data from ion retarding potential analyzers has serious pitfalls, and that these devices greatly disturb the surrounding plasma when measuring ion temperature. Finally, it is shown how the ion temperature can be accurately obtained from the characteristic of a cylindrical Langmuir probe in a rarefied plasma flow.

1. Introduction

The two prime methods of determination of ionospheric temperatures are *in situ* measurements using Langmuir-type probes on board satellites or rockets [1], and ground-based, radar measurements of incoherent backscatter [2]. Radar results are limited both geographically and in altitude resolution and range; moreover, when several ion species, and differing electron (T_e) and ion (T_i) temperatures are considered, interpretation of experimental data becomes difficult.

Significant comparisons between radar and probe T_e results have been achieved recently. Hanson et al. [3] and McClure and Troy [4] found probe-to-radar T_e ratios of 1.7 and 1.5 respectively. Similar results have been reported by Brace and McClure [5] and Carlson and Sayers [6]. A review of such comparisons has been given by Booker and Smith [7]. On the other hand, much smaller, although often systematic, disagreements have also been found [8—10]. In a check of self-consistency, Donley et al. [11] found that differences between three types of probes did not exceed 20%.

T_i data, and *a fortiori* radar and probe T_i comparisons, are much less abundant. Donley et al. [11] found a systematic, large (up to 100%) discrepancy between T_i values from planar and from spherical ion trap probes. Taylor and Wrenn [8], in a very limited comparison, found moderate, unsystematic differences between radar and spherical trap results. McClure and Troy [4] found a planar trap to radar T_i ratio of 1.4.

Carlson and Sayers [6] suggested that T_e differences could be due to a drift in the work function of the probes. Brace et al. [12] discussed and rejected this and several other sources of error in T_e probe results. Hoegy [13] observed that if the electron distribution function is not Maxwellian, probe and radar measurements should lead to different T_e values.

These discrepancies must be understood before real temperature variations of the ionospheric plasma can be studied.

2. Sources of Error in Present Temperature Measurement Analysis

2.1. Electron Temperature

T_e measurements are based on standard Langmuir probe theory. The I_p (plasma-to-probe current) versus V_p (probe-to-plasma potential) diagram is recorded for V_p negative. If the ion component of the current can be neglected, I_p is, under quite general conditions, independent of probe shape; for a Maxwellian electron distribution function [14]

$$I_p \propto \exp\,(e\,V_p/kT_e) \tag{1}$$

where $-e$ is the electron charge and k is Boltzmann's constant. A variety of probe shapes, both of the plain Langmuir and multiple grid (electron trap) types, have been used in the past.

We wish to show now that the geomagnetic field can lead to a systematic error in this method of finding T_e. Magnetic field effects have been largely ignored in probe theory because of the difficulty of their analysis. It is generally agreed nonetheless that an ambient magnetic field decreases the current in the $V_p > 0$ range, unless the electron Larmor radius l_e is large compared with the probe size; most probes do not satisfy this condition in the ionosphere, where $l_e \sim 1$ cm. On the other hand, it is frequently assumed that a magnetic field does not affect Eq. (1) ($V_p < 0$), even if l_e is not larger than the probe size. Recently, it has been shown that this is not generally true [15]. It was found there that the potential field did not increase monotonically from V_p on the probe to zero far from it; instead, a potential hill appeared along the magnetic field lines intersecting the probe. This is equivalent to a decrease of V_p by an amount equal to the potential overshoot (the positive value of potential at the top of the hill), the important point being that the overshoot *depends* on V_p. As in the case of the V_p-dependent drift of the probe work function [6], that dependence leads to an error in the value of T_e obtained in the usual manner. Since the potential hill is greater as V_p increases, it is clear that the value of T_e obtained will be larger than its real value.

2.2. Ion Temperature

To measure T_i in the ionosphere, multiple grid probes (ion traps) are used. The entrance grid G 1 and the collector C are either biased negative relative to the vehicle, or grounded to it; the vehicle itself has a potential $V_s < 0$ relative to the ionosphere. The suppressor grid G 3 is biased highly negative to turn back all electrons able to get past G 1, and to inhibit photo and secondary emission from the collector. G 2 is the retarding grid; its potential V_R is swept from slightly negative to highly positive to analyze the energy spectrum of incoming ions. The trap is oriented facing the vehicle velocity $-\boldsymbol{U}$ (planar trap).

To interpret trap measurements, a formula derived by Whipple [16] is always used. Whipple assumed that since the Debye length λ_D is smaller than the trap frontal dimension, and U is larger than the ion thermal velocity, a one-dimensional approach could be used to calculate the current I_c to the collector, as a function of V_R. If v_z is the velocity toward the trap of an ion, in the vehicle frame of reference, the undisturbed ion distribution function is proportional to $\exp[-m_i(v_z - U)^2/2kT_i]$, where m_i is the ion mass. Whipple then integrated over v_z between $(2eV_R/m_i)^{1/2}$ and $+\infty$ to get

$$I_c \propto 1 + \operatorname{erf} x + (2kT_i/\pi m_i U^2)^{1/2} \exp(-x^2), \tag{2}$$

$$x = [U - (2eV_R/m_i)^{1/2}](m_i/2kT_i)^{1/2}, \qquad V_R > 0.$$

As V_R increases, the right-hand side of Eq. (2) goes from about two to zero; as $(2kT_i/m_iU^2) \to 0$, I_c becomes a step function.

Although possible errors of Eq. (2) have been discussed in the literature [17—19], the most basic objection to the above formulation seems to have been overlooked: Consider V_R so large that practically no ions reach the collector. Obviously the ions repelled by G2 are ejected out of G1 with velocities close to $-U$. Inside this ion jet, and a few Debye lengths ahead of the trap, the ion density is $N_i \simeq 2N_e \simeq 2N_0$, where N_0 is the undisturbed plasma density. Taking into account that G1 has a transparency factor $\alpha < 1$, we would have $N_i \simeq (1 + \alpha^2)N_e \simeq (1 + \alpha^2)N_0$. As V_R is decreased, some ions begin to get through G2; for $V_R = m_i U^2/2e$, say, only half the ions are turned back and we would have $N_i \simeq (1 + \alpha^2/2)N_0$. The excess charge density inside the jet goes from $e\alpha^2 N_0$ to zero, as V_R decreases to zero. It should be noted that Eq. (2), for $(2kT_i/m_iU^2)^{1/2}$ small, is practically independent of T_i, unless a non-negligible fraction of the ions are turned back by G2; in fact, even at $V_R = m_i U^2/2e$, I_c only changes by 1% as T_i changes by 20%, for $(2kT_i/m_i U^2)^{1/2} = {}^1/_5$. (This point is rarely made clear in papers that show curve-fitting of Eq. (2) to experimental data.) Thus, over most of the time that the V_R sweep lasts, and certainly during the T_i-sensitive part of this sweep, enough ions are repelled by the trap to produce an excess ion density $N_i - N_0$ that is a non-negligible fraction of N_0. For typical V_R sweep times of the order of seconds, the length of the cylindrical tube (with the same cross section of grid G1) filled by the ion jet, is of the order of several kilometres! Obviously such a situation is impossible to maintain. Probably a large potential field will build up, spreading in *all* directions far away from the trap. Analysis of this problem is difficult, but certainly the real situation cannot resemble that envisaged in Eq. (2).

We have thus seen that an ion trap, measuring T_i, greatly disturbs the plasma far ahead of it. This is a general characteristic of the motion of a body moving through a plasma at a speed larger than $(2kT_i/m_i)^{1/2}$, but smaller than $(2kT_e/m_e)^{1/2}$, and *reflecting* ions. The ions in excess ahead of the body are those missing from the wake behind. When the body absorbs the ions, the perturbation ahead of the body disappears, and only the wake behind remains.

3. A Method to measure Ion Temperature

The current to a thin cylindrical probe immersed in a rarefied plasma flow is correctly given by orbital motion theory [14] when the probe radius r_p is small compared with the Debye length λ_D. For a flow velocity U such that

$kT_i/m_i \ll U^2 \ll kT_e/m_e$, and V_p large and negative ($-eV_p \gg kT_e, kT_i$), the current is given by

$$I_{p\infty} \simeq 2r_p l_p N_0 e (U^2 \sin^2\theta - 2eV_p/m_i)^{1/2} \tag{3}$$

where l_p is the probe length and θ is the angle between $\boldsymbol{U}$ and the probe axis; the ∞ subscript means that l_p is assumed so large that any end (finite l_p) effect will be negligible. Eq. (3) shows that $I_{p\infty}$ *decreases* smoothly as θ goes from $\pi/2$ to zero.

Recently, both satellite [20] and laboratory [21] probe measurements have detected a significant experimental disagreement with Eq. (3); the current measured was found to follow closely that equation, except at small values of θ, where the current showed a large *peak*. Although long probes were involved (l_p up to 820 r_p and 20 λ_D), it has been found that the disagreement is due to an end effect [20, 22]. An analysis of this effect has been developed recently [23].

The important point about the end effect is that both the height and the angular half-width of the peak are sensitive to T_i, thus allowing a measurement of this quantity. The single ion species analysis of [23] can be trivially extended to the case of several ion species, and it is also possible to choose values of V_p, l_p and r_p such that all constraint conditions derived in that paper are approximately satisfied; these constraints arise from the existence of the end effect itself, and from the simplifications required by the analysis. We find optimum values $l_p \sim 7$ cm, and V_p about $-20kT_e/e$; for r_p the value 0.028 cm, used frequently for ionospheric cylindrical-probe measurements [12], can be adopted.

For these values, and under the conditions prevailing in the ionosphere, the formulae of [23] can be simplified. For the height of the I_p peak we get

$$I_{p\max} = I_p(\theta = 0) \simeq 4\bar{\delta} r_p l_p N_0 e \left(\frac{-eV_p}{kT_i}\right)^{1/2} \times \sum_\alpha \frac{p_\alpha(-2V_p/m_\alpha)^{1/2} (\ln \sigma_\alpha^2 - 1)(l_n \sigma_\alpha^2)^{-1/2}}{[1 + 0.16(l_p/U)^2 4\pi N_0 e^2/m_\alpha]^{1/2}} \tag{4}$$

where the summation is over all ion species, and m_α and p_α are the mass and the relative concentration of species α, respectively (obviously $\Sigma p_\alpha = 1$); for the region of interest (350—1000 km), only H^+, H_e^+ and O^+ ions need be considered (N^+ being lumped together with O^+). We also have

$$\sigma_\alpha^2 = \frac{(2/\pi)(l_p/r_p)^2 \bar{\delta}(-eV_p/m_\alpha U^2)}{1 + 0.16(l_p/U)^2 4\pi N_0 e^2/m_\alpha}$$

and $\bar{\delta} = [\ln(\lambda_D/r_p) + Y(r_p/\lambda_D, -eV_p/kT_e)]^{-1}$ where Y is given in Fig. 1 of [23]; $4\bar{\delta}$ is always close to unity, and $\ln \sigma_\alpha^2$ lies between 5 and 10. For the angular half-width $\theta_{1/2}$ (the width of the peak at half-value of its maximum) the T_i dependence can be eliminated and we get

$$\frac{I_{p\max}}{2} \simeq \frac{(8/\pi)^{1/2}}{\theta_{1/2}} 4\bar{\delta} r_p l_p N_0 e \sum_\alpha \left(\frac{-eV_p}{m_\alpha U^2}\right)^{1/2} \times \frac{p_\alpha(-eV_p/m_\alpha)^{1/2} (\ln \sigma_\alpha^2 - 1)(\ln \sigma_\alpha^2)^{-1/2}}{[1 + 0.16(l_p/U)^2 4\pi N_0 e^2/m_\alpha]^{1/2}}. \tag{5}$$

Before obtaining T_i from Eq. (4) it is necessary to know N_0, the satellite potential (and thus V_p), and p_α ($\alpha = H^+, He^+, O^+$). The first two quantities can be obtained by means of a second cylindrical probe, using a well-known method (see [12] for references on this method). That probe should be oriented approximately perpendicular to $\boldsymbol{U}$ and should be biased highly negative for part of the time, so that Eq. (3) can be applied to give a linear relation between the concentrations. Two other linear relations are given by $\Sigma p_\alpha = 1$ and Eq. (5). T_i follows then from Eq. (4). It should be noted that to obtain this quantity it is only necessary to make an order of magnitude estimate of T_e.

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